Global Carbon Data Management and Synthesis Project

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This project report combines three closely linked OCO projects:

Project 1: CLIVAR/ CO_2 Repeat Hydrography Program CO_2 Synthesis Science Team
Project Manager: Richard A. Feely[1]

Project 2: End-to-end Data Management System for Ocean pCO_2 Measurements
Project Manager: Steve Hankin[1]

Project 3: Understanding the Temporal Evolution of the Global Carbon Cycle Using Large-Scale Carbon Observations
Project Manager: Christopher L. Sabine[1]

PROJECT SUMMARY

The ocean plays a critical role in the global carbon cycle as it is a vast reservoir of carbon, naturally exchanges carbon with the atmosphere, and consequently takes up a substantial portion of anthropogenically-released carbon from the atmosphere. Although the anthropogenic CO_2 budget for the last two decades, i.e. the 1980s and 1990s, has been investigated in detail (Prentice et al., 2001), the estimates of the oceanic sink were not based on direct measurements of changes in the oceanic inorganic carbon.

Recognizing the need to constrain the oceanic uptake, transport, and storage of anthropogenic CO_2 for the anthropocene and to provide a baseline for future estimates of oceanic CO_2 uptake, two international ocean research programs, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), jointly conducted a comprehensive survey of inorganic carbon distributions in the global ocean in the 1990s (Wallace, 2001). After completion of the US field program in 1998, a five year effort – the Global Ocean Data Analysis Project (GLODAP) - was begun to compile and rigorously quality control the US and international data sets including a few pre-WOCE data sets in regions that were data limited (Key et al., 2004). Although these data have improved our understanding of the spatial distributions of natural and anthropogenic carbon in the ocean, they have yet to be fully exploited to examine the mechanistic controls on these carbon distributions or to understand the temporal patterns of variability.

Most of the approaches used to estimate anthropogenic CO_2 in the oceans are based on assumptions of steady state circulation and constant biology. It is becoming increasingly apparent that these assumptions may not hold in a global change environment. The most important component of an assessment of ocean biogeochemical change, whether of natural or anthropogenic origin, is high-quality observations. The WOCE/JGOFS data set provides an important point of reference for ocean carbon studies. Many other useful data sets have not been analyzed in such a context, however because there has not been a coordinated effort to bring these data together and no data

management system to make navigation and exploitation of these data convenient.

The NOAA Office of Climate Observation's Carbon Network (hydrographic sections, underway pCO_2, and CO_2 moorings) is a valuable contribution to the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). It is not sufficient, however, simply to collect and archive the data, if we expect the data to improve our understanding of the global carbon cycle and the role of the ocean in climate change.

Recognizing the need for proper data management and synthesis, NOAA's Office of Climate Observations (OCO) has funded several projects to manage and perform an initial interpretation of the data collected from the Carbon Network. Because three of these OCO projects are very closely linked and often work together to generate an end product, we have combined the projects into one management and synthesis project as of this report. The goal of the Global Carbon Data Management and Synthesis Project is to work together with the OCO carbon measurement projects to take the fundamental carbon observations and turn them into products that are useful for scientists and the public for understanding the ocean carbon cycle and how it is changing over time. This effort ranges from ensuring that the observations are of the highest quality and are mutually consistent with each other to combining the observations into a common data set that is available and easy for the community to use and explore to evaluating the time rate of change in global ocean carbon uptake and storage. This project brings together ocean carbon measurement experts, information technology experts and data managers to ensure the most efficient and productive processing possible for the OCO carbon observations.

BACKGROUND

Although ocean carbon uptake and storage plays a critical role in influencing global climate change, the community involved in studying ocean carbon is not as large nor is it as geared towards operational activities as the climate and physical oceanographic communities. There are no operational data centers ready to take the basic carbon observations and turn them into products like the climate forecasts or reanalysis products. As a consequence, the ocean carbon community is expected to provide the public with advanced analysis products, like global CO_2 flux maps or maps of the patterns of CO_2 uptake and storage, in addition to the basic observations. The generation of these products is the objective of this project, but it is a somewhat complicated process because it involves several data manipulation steps and coordination with many other investigators. For this report we divide the process into three categories: measurement coordination and initial quality control, data management and contextual quality control, then synthesis and interpretation.

The number of observations needed to address a global issue like ocean carbon uptake and storage is well beyond the capabilities of one lab or even one country. Thus, there are many laboratories from several countries involved in the assessment of global carbon distributions. To produce the greatest return on the US investment in ocean carbon measurements, we must ensure that all of the US laboratories are using consistent cutting-edge techniques, are assessing and documenting the data quality, and are coordinating the US measurements with the international programs so that once the data are combined we get the most extensive coverage possible. This is the measurement coordination and initial quality control portion of this project. Once the data are collected and the initial data quality has been documented, then the data must be pulled into a data management system that brings the individual laboratory data sets together into a common data base. At this point the data sets are large enough that it is awkward to manipulate without a data visualization program. Once the data set is assembled, the internal consistency of the data relative to any crossing or historical data must be checked. This is the data management and contextual quality control portion of the project. The final step in the process is taking the data set and examining it to understand how the current carbon distributions have changed and the mechanisms responsible for the observed changes. This last step is an evolving set of analyses that is continually improved and adapted as additional data is added to the data set. Each of these three steps is related and often requires iterative refinements of the previous steps to develop the final products leading to improved estimates of ocean uptake and storage.

The OCO ocean carbon network makes two basic types of observations: surface CO_2 observations with ships of opportunity and moorings and water column carbon observations with repeat hydrography cruises. The Global Carbon Data Management and Synthesis Project addresses both observation types. Because surface observations are collected in a different manner and have different requirements for developing the final product than the repeat hydrography data, the data management for these two data types is discussed separately. The activities and accomplishments for both data types in FY06 are discussed below.

ACCOMPLISHMENTS

Measurement Coordination and Initial Quality Control

Repeat Hydrography

Annual CO_2 science team meetings held by the Department of Energy (DOE) proved to be a valuable contributor to the coordination and quality control of the WOCE/JGOFS global survey data collected in the 1990s. These meetings provided an opportunity to discuss past data quality, potential refinements of the methods, and plans for future cruises (e.g. coordination of shipping, needs for reference materials, personnel issues). Learning from that approach, the scientists involved in the US CLIVAR/CO_2 Repeat Hydrography Program regularly meet to discuss measurement coordination and data quality issues. The last formal meeting of the measurement group was organized by Feely in September 2005 in Boulder, CO. This meeting examined the data quality issues for the recently completed A16S and P16S cruises as well as plans for future cruises including the NOAA led 2006 P16N cruise. Additional informal meetings of the group were held at the Fall AGU meeting in December, 2005 and the Ocean Sciences meeting in February, 2006. The group remains in frequent contact via email and phone and also works closely with the US CLIVAR/CO_2 Repeat Hydrography Steering committee through Richard Feely (co-chair), Gregory Johnson (committee member), Frank Millero (committee member) and Christopher Sabine (committee member).

The US activities are also coordinated with the international carbon community through the International Ocean Carbon Coordination Project (Christopher Sabine, chair). Recognizing the immediate need for global-scale coordination of carbon observations and research efforts to achieve the goal of a global synthesis, the IOC-SCOR Ocean CO_2 Panel (http://www.ioc.unesco.org/iocweb/co2panel/) and the Global Carbon Project (GCP; http://www.globalcarbonproject.org/) initiated the International Ocean Carbon Coordination Project in 2002 (IOCCP; http://www.ioc.unesco.org/ioccp/) to: (1) gather information about on-going and planned ocean carbon research and observation activities, (2) identify gaps and duplications in ocean carbon observations, (3) produce recommendations that optimize resources for international ocean carbon research and the potential scientific benefits of a coordinated observation strategy, and (4) promote the integration of ocean carbon research with appropriate atmospheric and terrestrial carbon activities. It is through the workings of the IOCCP and international CLIVAR that international coordination of data management, data synthesis and scientific interpretation of the global repeat sections results is being implemented.

In addition to overall coordination activities, the Global Carbon Data Management and Synthesis group has been working to ensure the timely submission of fully documented data to the Carbon Dioxide Information Analysis Center (CDIAC) for release to the public. CDIAC is also working closely with the IOCCP to help facilitate international coordination of cruises by creating a clickable map of completed CLIVAR repeat hydrography cruises (http://cdiac.ornl.gov/oceans/RepeatSections/repeat_map.html) that is linked to the IOCCP map of planned repeat hydrography cruises (http://ioc.unesco.org/ioccp/Hydrography/Hydro_Map.htm). Thus far, CDIAC has received and processed 12 international data sets from the repeat hydrography program. Data from two US cruises, A16N and A16S, have already been published as numeric data packages (NDP-085 & NDP-087) and are available in both hard copy and electronic (HTML) format from CDIAC.

Within this last fiscal year, we have produced two comprehensive cruise reports for the NOAA led cruises: A16S in 2005 (http://www.aoml.noaa.gov/ocd/gcc/a16s/) and P16N in 2006 (http://whpo.ucsd.edu/data/co2clivar/pacific/p16/p16n_2006a/index.htm). A separate report on the internal consistency of the carbon system parameters on A16S was published with the CDIAC NDP-087 (Wanninkhof et al., 2006a). Internal consistency calculations have been performed for the A16 and P16N cruises, taking advantage of the high quality pH, pCO_2, DIC, and TA data. The comparisons show that to fully constrain the carbon system, measurements of water column pCO_2 and/or pH are critical. These results suggest that the pCO_2 and/or pH measurements should be elevated to a level 1 parameter (from the current level 2 status). This proposal will be brought to the US CLIVAR/CO_2 Repeat Hydrography Steering Group and is one clear example how subsequent analysis of the data can feed back to decisions on measurement protocols.

The group is also working with Dr. Robert Byrne (University of South Florida) and others to evaluate new instruments capable of making high precision ship-board carbon measurements. A paper describing a novel underway system to measure pH, pCO_2, and DIC, used for the first time on a major cruise, A16S, is in preparation (Wang et al., in prep). Analysis was performed to compare the underway data with the discrete data obtained at the stations as a robust indicator of system performance.

Surface CO_2

A meeting of the NOAA funded surface pCO_2 investigators was organized by Wanninkhof in Miami, FL early in FY06 to discuss standardization of measurement protocols and data processing routines (http://www.aoml.noaa.gov/ocd/gcc/pco2/). As part of the meeting there was a round robin exchange of shipboard data between the groups to compare data reduction software. This exercise proved to be very useful for identifying the impact of differing data reduction routines. Many important agreements were reached that should improve the uniformity of data products coming from these groups in the future. The participants also discussed future improvements to the systems, agreements on running the systems in coastal regions, and efforts to work with a private company, General Oceanics, to build standardized instrumentation for the community. Working with the IOCCP, these agreements have been provided to the international community in an effort to promote a more uniform handling of surface pCO_2 data in the international community.

A joint meeting of the surface CO_2 group and the repeat hydrography group is planned for FY07 because there is some overlap in the coordination of all these measurements. This joint meeting should also promote a more integrated approach to data management and synthesis.

Data Management and Contextual Quality Control

Repeat Hydrography

All of the US CLIVAR/CO_2 Repeat Hydrographic data is managed by CDIAC and the CLIVAR and Carbon Hydrographic Data Office (CCHDO) at Scripps. As a world data center, CDIAC also collects and manages carbon data from many international cruises. Alex Kozyr from CDIAC is an active member of the Global Carbon Data Management and Synthesis Project and has been working with the group to improve the utility of the CDIAC data sets. The latest advancement is the development of a Web-Accessible Visualization and Extraction System (WAVES). This is a data management system that allows one to subset a large oceanographic data set based on a variety of spatial, temporal, or meta-data criteria (Figure 1). This program was developed at CDIAC with DOE funding but is benefiting the NOAA data management project. Currently, all of the CDIAC water column measurements are available through the system. The CDIAC surface CO_2 data should be completed and opened for public use in 2007.

In addition to the individual cruise files maintained at CDIAC, Robert Key at Princeton University also maintains a collection of cruises that have been merged together for the group's scientific analyses. The WOCE/JGOFS version of this collection is called GLODAPv1.1 and has been described in the literature (Key et al., 2004; Sabine et al., 2005). Over the past year significant progress has been made on the construction of a new data base which includes a temporal component. In large part the mechanics of constructing this data base are very similar to those used for GLODAPv1.1. The primary difference is that the new collection is based largely on cruise results generated by the European ocean carbon community. These data have not previously been available for use by U.S. scientists. Also significant is the fact that the vast majority of these new data are from the northern North Atlantic. Coverage of that area in GLODAPv1.1 was sparse to none.

The original "CARINA" collection of European cruises was transferred to

CDIAC for archiving and subsequently to Princeton for synthesis. The initial synthesis phase has consisted of primary quality control and collection of metadata. During the first two years of this effort Key attended all the CARBOOCEAN meetings (participation funded by CARBOOCEAN) and developed a close collaboration with the European community. This interaction combined with the initial data synthesis directly resulted in a significant increase in the data collection from 30 to 80 cruises (by mid summer 2006). In many cases the data from the new cruises is significantly better than the original collection. Primary quality control of all measured parameters from these 80 cruises and metadata collection has been largely completed. The task continues because previously unknown (yet relevant) data are continually being "discovered" for existing cruises and new cruises are still being added.

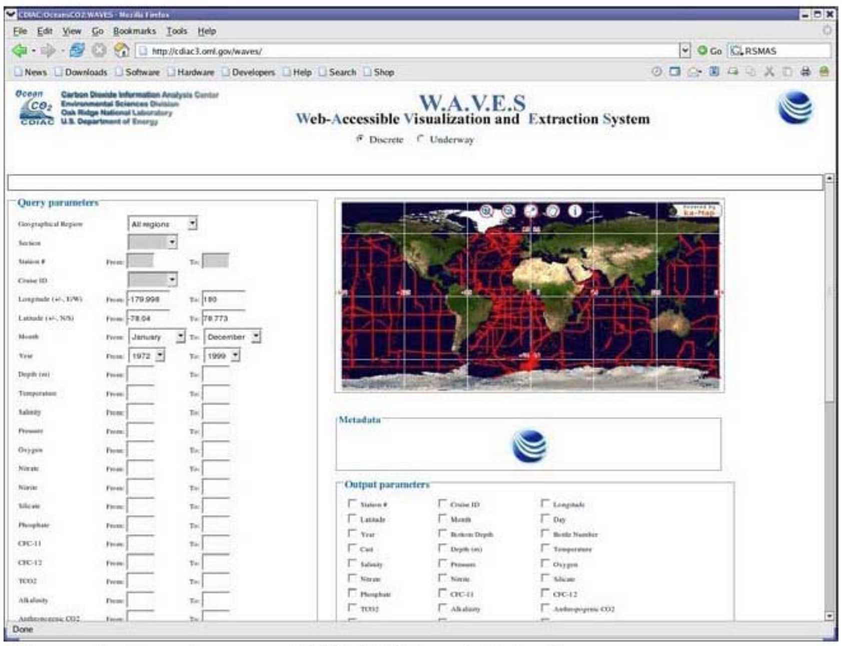

Figure 1. Front page of WAVES web interface.

CLIVAR data collection and processing has been progressing smoothly. With a couple of notable exceptions, all of the CLIVAR carbon data have been submitted to both CCHDO and CDIAC well ahead of the minimum time requirement of this program. The new U.S. data (and the Japanese CLIVAR data) have been extremely high quality. The combination of initial high data quality together with the fact that the Carbon Data Management and Synthesis group has extensive experience working together has made the quality control of these data almost routine. For example, Figure 2 shows a recent comparison of data from two CLIVAR/CO_2 Repeat Hydrography cruises in the North Pacific: the 2004 P2 cruise along 30°N and the 2006 P16N cruise along 152°W. The deep water values for temperature, salinity, DIC and total alkalinity agree very well between these cruises. Figure 3 also shows a comparison between the 2006 P16N data and the previous occupation of this line in 1991 along the relatively deep 41.425-41.450 σ_3 isopycnal surface. There appear to be no significant differences in any of the parameters examined at this surface indicating that the data are consistent with each other. Over determination of the carbon system on all NOAA led CLIVAR/CO_2 Repeat Hydrography cruises has been extremely beneficial both for technical issues and scientific reasons. We encountered one major data issue during the past year when NODC imported (from CCHDO) and distributed raw shipboard carbon data from three cruises. However, the problem was quickly discovered by A. Kozyr (CDIAC) and steps have been taken to assure that this does not happen again.

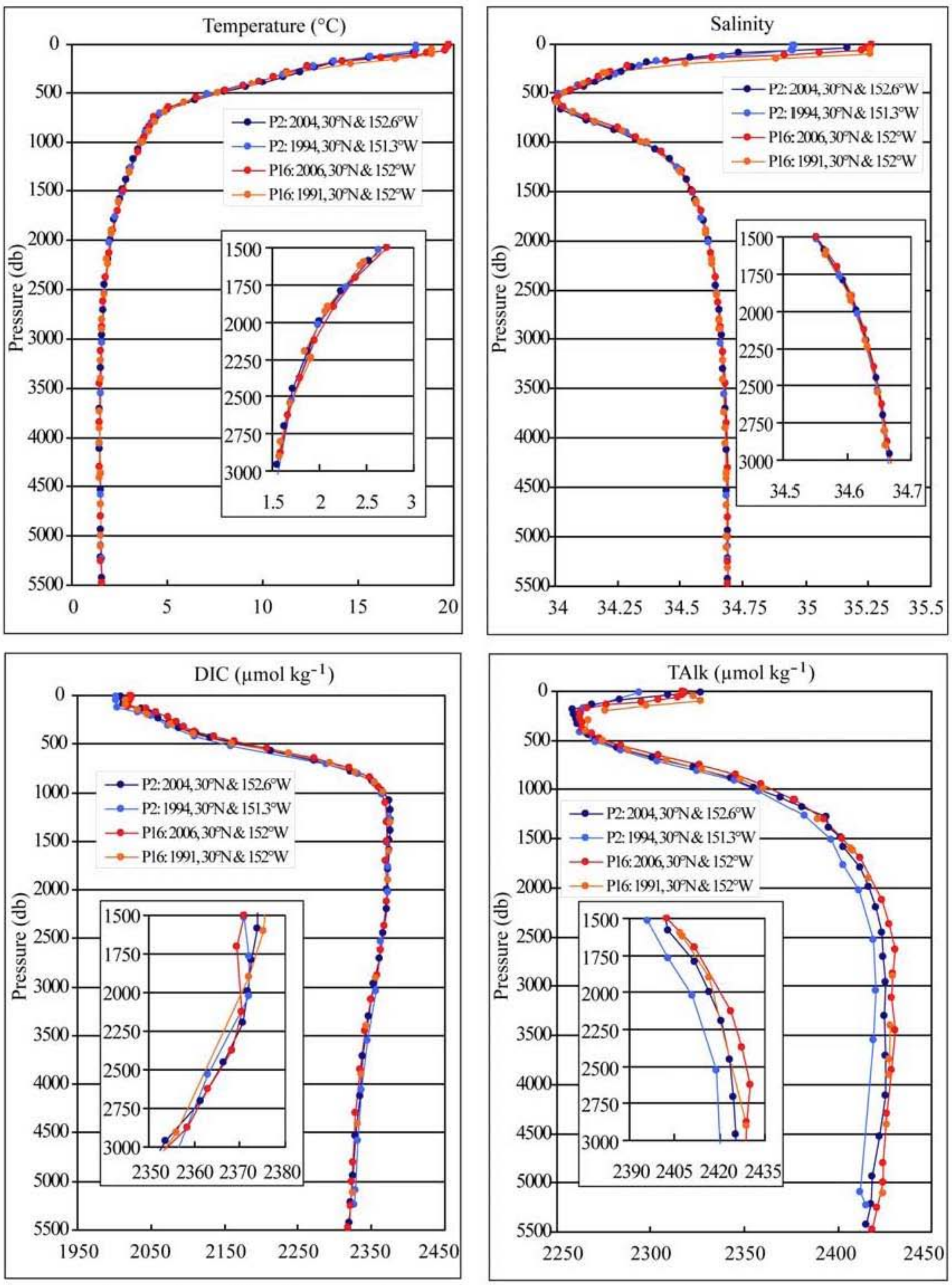

Figure 2. Comparison of profiles from stations near the intersection of P2 and P16N.

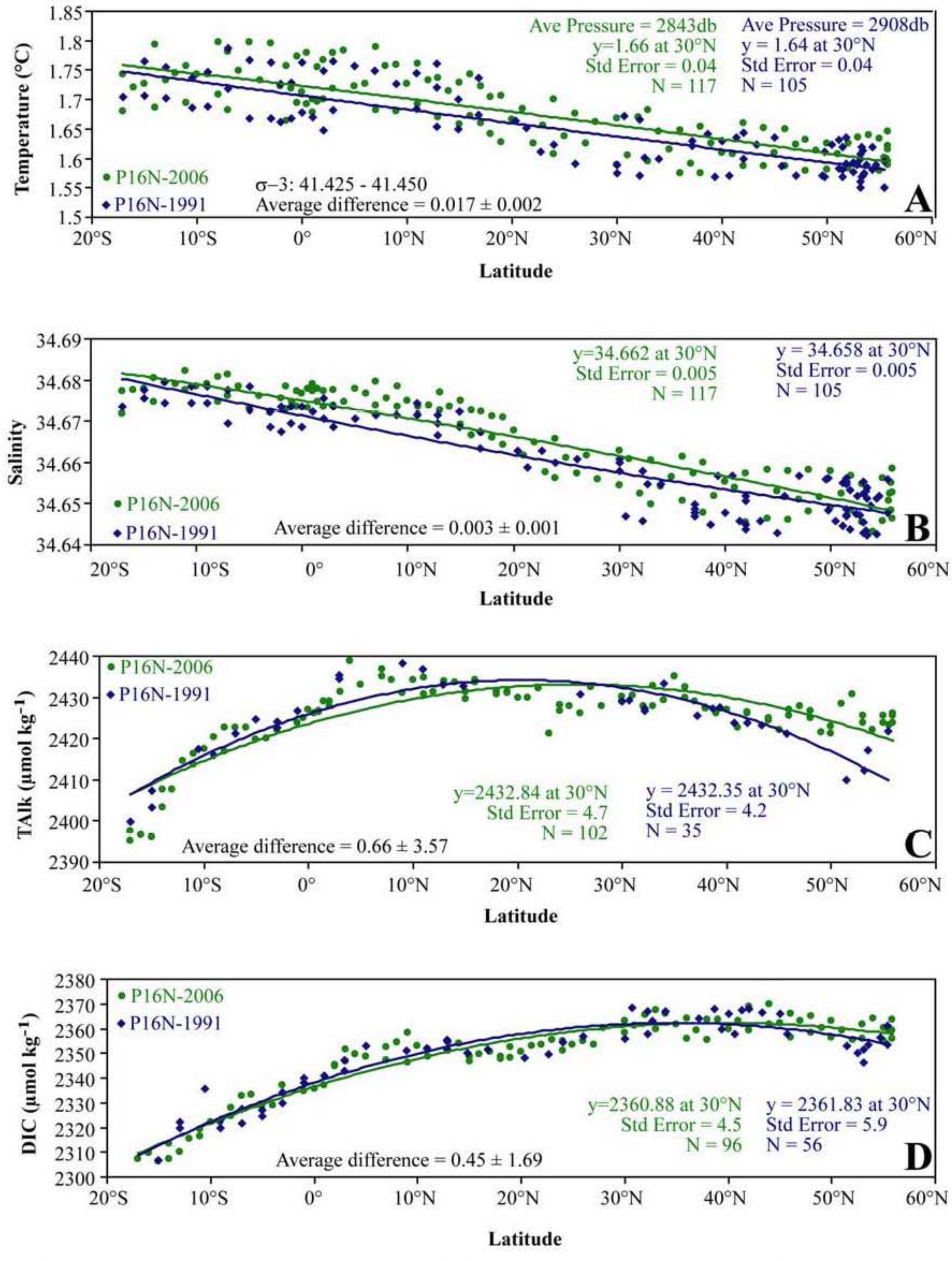

Figure 3. Comparison of 1991 P16N data with 2006 P16N data along 41.425-41.450 σ_3 isopycnal surface.

Surface CO_2

The PMEL data management infrastructure (software and hardware) is now in place to efficiently handle existing and new surface CO_2 datasets. Development of the Live Access Server (LAS) to make meaningful manipulations and displays of surface CO_2 measurements has been ongoing at PMEL for several years under Hankin's guidance. A prototype of this system based on the new LAS software has been populated with 1.2 million data records from the PMEL, AOML, and LDEO archives. The advantages of an integrated data management approach are already bearing fruit as the automated ingestion process was able to identify inconsistencies in several of the data sets such as duplicate records, out-of-range values, invalid dates, etc. Interaction between Dr. Callahan (PMEL) and the data providers resulted in corrections to data files that had been considered 'final'.

The Ocean Carbon Data Management System (OCDMS) at PMEL takes advantage of the latest LAS code that has been completely rewritten in the last two years with a new, more robust design and using recently available technologies. The new LAS code will allow for easier maintenance, installation and product development going forward. Many enhancements were made to the LAS user interface and output products so that individual cruises may be identified by name on plots. These plots show multiple cruise tracks which may be individually selected for inspection of metadata, single cruise visualization or subsetting. Subsampled versions of the complete database were created to optimize LAS performance when users request large regions of space and time. It is now possible to interactively produce LAS plots showing all data from all cruises – a significant achievement for a database of this size.

Once the OCDMS has been thoroughly tested by the Carbon Data Management and Synthesis group, it will be replicated at CDIAC for large-scale community use. Efforts are currently underway to ingest the recently acquired Takahashi data set which contains in excess of 3 million data points. While these data will be preserved as a unique data set, the LAS system will allow users to subset and explore the data efficiently.

CDIAC and the rest of the group are also working with the international community through the IOCCP to standardize data and metadata reporting for surface CO_2 data. However, not all investigators measure exactly the same parameters. Calculations to convert measured values to standard units have not always been well documented. In an effort to support this move towards standardized reporting, AOML, PMEL, and LDEO have reformatted all of their historical data to be consistent with the internationally agreed upon formats.

CDIAC has generated a web site with clickable maps showing past and current Volunteer Observing Ship (VOS) lines (http://cdiac.ornl.gov/oceans/VOS_Program/VOS_home.html) and CO_2 mooring locations (http://cdiac.ornl.gov/oceans/Moorings/moorings.html). These maps are closely linked with IOCCP maps showing current and planned VOS lines and CO_2 moorings.

Synthesis and Interpretation

Repeat Hydrography

The repeat hydrography cruises have received a lot of attention in the scientific community. All of the members of the Global Carbon Data Management and Synthesis group have given talks at a wide variety of meetings based on the repeat hydrography data and papers are starting to come out presenting some of the results. This past year a special session was organized by L. Talley and R. Feely at the AGU/ASLO Ocean Sciences meeting in Honolulu, Hawaii titled "Decadal Variations in Ocean Interior Circulation and Biogeochemistry: Results From the CLIVAR/CO_2 Repeat Hydrography Program". Feely has organized a similar session at the Fall AGU meeting this December. He has also published an article in EOS describing the repeat hydrography program and summarizing the results to date (Feely et al., 2005). The community has recognized that these cruises are a great contribution to our improved understanding of ocean carbon changes.

Now that we are approximately half way through the first global repeat hydrography survey, many international synthesis and interpretation efforts are developing. Our group has been actively involved in several efforts including an Atlantic synthesis meeting in Laugarvatn, Iceland in June 2006, discussions of a Pacific synthesis at the PICES annual meeting in Yokohama, Japan in October 2006, and discussions of an Indian Ocean synthesis at the SIBER meeting in Goa, India in October 2006. There have also been recent email discussions of forming a Southern Ocean synthesis activity through CARBOOCEAN including members of our group. Our NOAA project is one of the only organized groups that are affiliated with synthesis activities in all of the major ocean basins.

Our group has been actively sought out to participate in the synthesis activities because we have valuable experience from our GLODAP synthesis of the WOCE/JGOFS data, because we have important data holdings to contribute to a synthesis effort and because we are seen as leaders in promoting and organizing data synthesis activities. We have been actively involved in data synthesis for many years and have been important contributors to a growing realization among scientists that interpretation of the repeat hydrography data will not be as straightforward as initially thought.

During the initial GLODAP synthesis the steady state assumption (in one form or another) was core to many of the analyses. Subsequent analysis by this group and many others has demonstrated that our assumptions were reasonable under the conditions we had for that synthesis. Paramount among these was the simple fact that the time separation between WOCE and previous measurement programs was 15-25 years. Over that time span changes due to the invasion of anthropogenic carbon effectively masked any changes due to biology or physics. CLIVAR is repeating WOCE/JGOFS lines with a time separation of about 10 years. Over this time frame the signal to noise ratio is much smaller and we are now strongly focused on change rather than simply asking distribution and inventory questions. In other words, the scientific analysis is significantly more difficult than anyone imagined.

We initially hoped that a reasonable estimate of the change in anthropogenic carbon could be obtained simply by repeating measurements along the WOCE/JGOFS sections then using either simple Multiple Linear Regressions (MLR) or subtraction to find the decadal change. Either of these techniques do show the absolute change in inorganic carbon, however a significant fraction of that change is due to processes other than simple invasion of the anthropogenic signal. Probably the two most important factors which were not initially considered are interannual circulation variations and changes in oxygen ventilation. Recently Feely, Sabine and Wanninkhof have worked with other researchers to develop various new analysis techniques including oxygen corrections and MLR variants to isolate the anthropogenic component. For example, Figure 4 shows a series of sections from the P16 line along 152°W in the central Pacific. This line, completed in 2006, was last occupied in 1991. The top plot shows a section of the observed change in dissolved inorganic carbon (DIC) during the 15 years between cruises. These results are based on a multiple linear regression to remove small variations in the water mass locations. Figure 4B shows the change in apparent oxygen utilization (AOU) along the section. These changes in AOU could result from changes in biological production/decomposition, from changes in water mass age, or from changes in oxygen ventilation at the surface. Figure 4C shows the AOU change converted to carbon units based on a Redfield C/O ratio of 117/170. Figure 4D is the difference between the observed carbon changes (4A) and the non-gas exchange impacts on carbon (4C). This difference should represent the anthropogenic CO_2 uptake in the Pacific over the last 15 years. We are still working to validate these preliminary results, but the initial conclusion is that the ocean carbon cycle is responding to more than just the simple invasion of anthropogenic CO_2 and these other processes can be of the same order of magnitude as the anthropogenic signal.

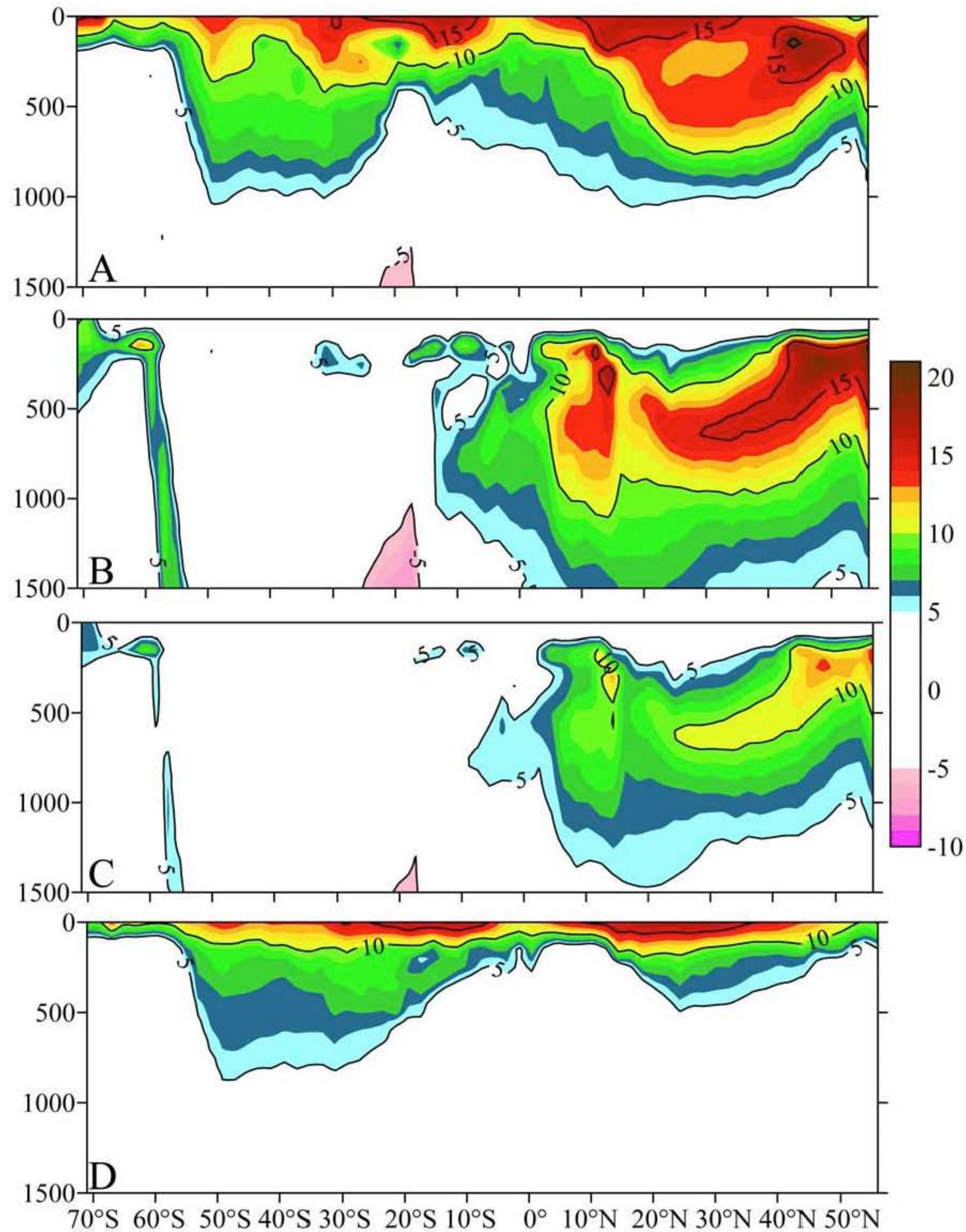

Figure 4. Sections of (A) observed DIC change, (B) changes in apparent oxygen utilization rate, (C) DIC change from AOU based on Redfield conversion from oxygen to carbon, and (D) anthropogenic DIC change (observed DIC – AOU based DIC change) between 1991 and 2006 along P16 (150°W).

Members of the Global Carbon Data Management and Synthesis group have also been involved in model-data comparisons, further evaluations of the ΔC* based anthropogenic CO_2 distributions and the evaluation of alternative independent approaches for estimating anthropogenic CO_2 total inventories. As part of a continuing effort to increase the global carbon database, Peng has been working to evaluate historical carbon data sets relative to the WOCE/JGOFS data. The carbon data collected during the GEOSECS program in early 1970s represent the first systematic survey of inorganic carbon parameters on a global scale. These data can provide a critical time period for evaluating changes in ocean carbon inventory relative to later cruises. It is essential, however, that the historic GEOSECS data set is consistent with recent high quality carbon data collected using improved measuring techniques and validated with the use of reference materials. Re-evaluation of GEOSECS carbon data in the Atlantic Ocean by examining properties in deep water at crossover stations between GEOSECS and WOCE cruises shows that DIC measurements made during the GEOSECS program are systematically higher than those made during the WOCE/JGOFS global CO_2 survey (Figure 5). These systematic changes, however, vary from one GEOSECS expedition to the next. Atlantic DIC offsets range from 5 ± 5 µmol kg^{-1} south of 15°S to 27 ± 9 µmol kg^{-1} north of 15°N.

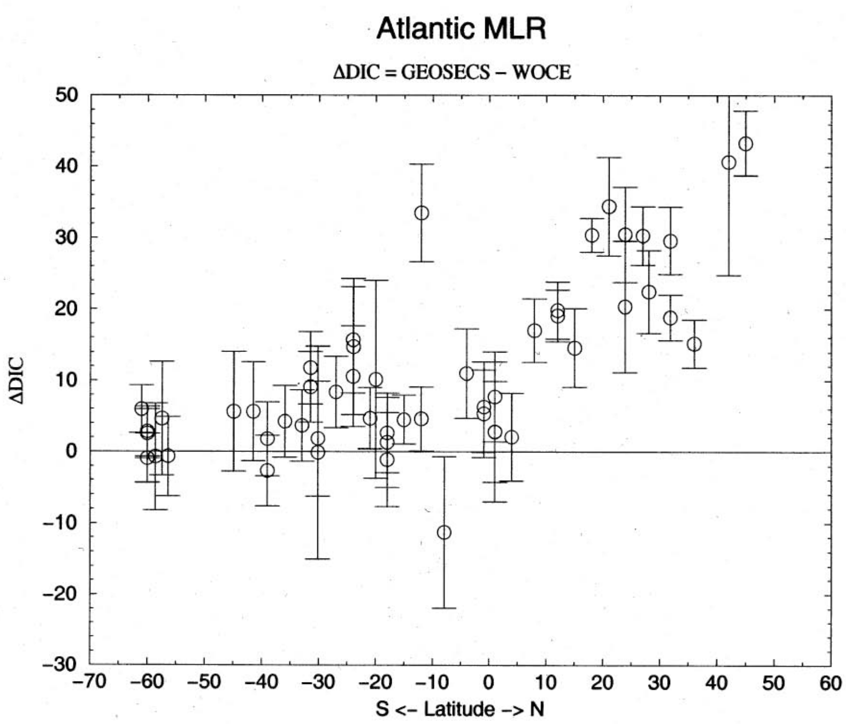

Figure 5. Systematic offsets of DIC in the Atlantic between GEOSECS and WOCE as determined by MLR method using crossover station deep-water properties.

Using MLR approaches to evaluate the water column changes in DIC between the bias corrected GEOSECS and WOCE cruises gives uptake estimates ranging from 0.28 mol m^{-2} yr^{-1} for the eastern South Atlantic (south of 15°S) to 0.97 mol m^{-2} yr^{-1} for the eastern North Atlantic (north of 15°N). The uncertainty of these estimates is high due to insufficient GEOSECS data and because the quality of these baseline data is not as good as recent WOCE data, but the observed patterns in uptake will provide valuable information when compared to recent re-occupations in these regions.

Surface CO_2

One of the premier ocean data products used in global carbon cycle research has been the global air-sea CO_2 flux climatology by Taro Takahashi (LDEO). The first climatology was published in 1990 and contained less than half a million data points (Tans et al., 1990). Over the years, the Takahashi climatology has been updated and revised. The most recent climatology, published in 2002, contained approximately one million data points (Takahashi et al., 2002). With valuable contributions from the NOAA VOS and mooring program, the Takahashi data set is now over three million data points. The Carbon Data Management and Synthesis group is working with Takahashi to prepare the latest climatology, which hopefully will be submitted within the year.

Although the climatology is a valuable contribution, the first step to decrease the uncertainty in ocean CO_2 uptake is to determine the natural variability in air-sea CO_2 fluxes. This can be done with models or through an innovative technique of utilizing the Takahashi CO_2 climatology and annual changes in sea surface temperature. This method takes advantage of the strong and regionally unique correlation of SST with surface water pCO_2. The method was first proposed in Lee et al (Lee et al., 1998) and expanded upon in Park et al. (Park et al., 2006). We have utilized the algorithms provided in Park et al. and global SST products from AVHRR (through the NOAA Coastwatch program) and winds from the NCEP assimilation product to estimate the global air-sea fluxes on annual timescales. The results of the analysis of Park et al. and our effort are shown in figure 6. While the trends during the period of overlap are the same there is an appreciable offset in the datasets that is attributed to use of different wind speed products. Using data obtained by the OCO funded pCO_2 on moorings and ships projects, and a pending proposal to GCC we will improve the regional pCO_2-SST relationships and decrease the uncertainty in the estimates.

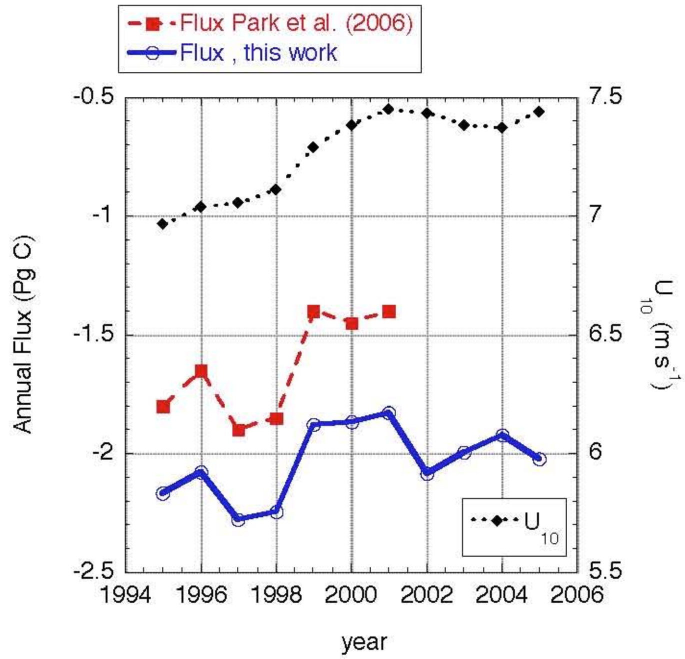

Figure 6. Preliminary analysis of interannual variability of air-sea CO_2 fluxes based on SST anomalies from 1995-2005. The average global wind used, U_{10}, is shown on the right axis. The recent analyses of Park et al. 2006 is shown as comparison.

In an effort to improve the algorithms used in the flux maps described above, we are working to develop improved regional empirical relationships between surface seawater pCO_2 and parameters that can be observed with satellites. PMEL has recently improved the algorithms for the equatorial Pacific, a region with very large fluxes of CO_2 out of the ocean but also large interannual variability (Feely et al., 2006). AOML has been examining empirical relationships for the eastern Caribbean where sea surface temperature appears to be a good proxy for surface water pCO_2 (Wanninkhof et al., 2006b). We anticipate implementing these new algorithms in future calculations of the CO_2 flux maps in an effort to reduce the overall uncertainty.

REFERENCES

Feely, R.A. et al., 2006. Decadal variability of the air-sea CO_2 fluxes in the equatorial Pacific Ocean. J. Geophys. Res. Ocean, 111(C08, C08S90): doi: 10.1029/2005JC003129.

Feely, R.A., Talley, L.D., Johnson, G.C., Sabine, C.L. and Wanninkhof, R., 2005. Repeat hydrography cruises reveal chemical changes in the North Atlantic. Eos, Transactions of the American Geophysical Union, 86(42): 399, 404-405.

Key, R.M. et al., 2004. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). Global Biogeochemical Cycles, 18(4). Lee, K.R., Wanninkhof, R., Takahashi, T., Doney, S. and Feely, R.A., 1998. Low interannual variability in recent oceanic uptake of atmospheric carbon dioxide. Nature(396): 155-159. Park, G.-H., Lee, K., Wanninkhof, R. and Feely, R.A., 2006. Ocean data-based estimates of recent year-to-year variability of oceanic uptake of CO2. J Geophys. Res(111): doi:10.1029/2005JC003090.

Prentice, I.C. et al., 2001. The carbon cycle and atmospheric CO_2. In: J.T. Houghton and D. Yihui (Editors), Climate Change: The Scientific Basis, Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 183-287.

Sabine, C.L. et al., 2005. Global Ocean Data Analysis Project (GLODAP): Results and Data., ORNL/CDIAC-145, NDP-083, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN. 110pp.

Takahashi, T. et al., 2002. Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. Deep-Sea Research Part Ii-Topical Studies In Oceanography, 49(9-10): 1601-1622.

Tans, P.P., Fung, I.Y. and Takahashi, T., 1990. Observational Constraints on the Global Atmospheric CO_2 Budget. Science, 247: 1431-1438.

Wallace, D.W.R., 2001. Storage and transport of excess CO_2 in the oceans: The JGOFS/WOCE Global CO_2 Survey. In: G. Siedler, J. Church and J. Gould (Editors), Ocean Circulation and Climate: Observing and Modeling the Global Ocean. Academic Press, San Diego, CA, pp. 489-521.

Wang, Z.A., Liu, X., Byrne, R.H. and Wanninkhof, R., in prep. Simultaneous Spectrophotometric Flow-Through Measurements of Multiple Inorganic Carbon Parameters in Seawater: At-sea Test and Comparison.

Wanninkhof, R. et al., 2006a. Carbon dioxide, hydrographic and chemical data obtained during the R/V Ronald H. Brown repeat hydrography cruise in the Atlantic Ocean.

Wanninkhof, R., Olsen, A. and Trinanes, J., 2006b. Air-Sea CO_2 Fluxes in the Caribbean Sea from 2002-2004, The 37th International Colloquium on Ocean Dynamics: Gas Transfer at Water Surfaces. in press.

FY06 PUBLICATIONS AND REPORTS

Arrigo, K., H. Bange, R. Feely, N. Gruber, D. Hansell, G. Herndl, K. Lee, T. Johannessen, K. Johnson,
A. Körtzinger, N. Metzl, T. Saino, and B. Stephens, *Joint SOLAS-IMBER Ocean Carbon Research: Implementation Plan*. IMBER Report No. 1/SOLAS Report, International Council for Science, Scientific Committee on Oceanic Research, 45 pp, 2006.

Bates, N.R., A.C. Pequignet, and C.L. Sabine, Ocean carbon cycling in the Indian Ocean: I. Spatiotemporal variability of inorganic carbon and air-sea gas exchange. *Global Biogeochem. Cy.*, 20(3), GB3020, doi: 10.1029/2005GB002491, 2006.

Bates, N.R., A.C. Pequignet, and C.L. Sabine, Ocean carbon cycling in the Indian Ocean: II. Estimates of net community production. *Global Biogeochem. Cy.*, 20(3), GB3021, doi: 10.1029/2005GB002492, 2006.

Caldeira, K., M. Akai, P. Brewer, B. Chen, P. Haugan, T. Iwama, P. Johnston, H. Kheshgi, Q. Li, T. Ohsumi, H. Pörtner, C. Sabine, Y. Shirayama, and J. Thomson, *Ocean Storage. Chapter 6 in IPCC Special Report on Carbon Dioxide Capture and Storage*, Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.), Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 277–317, 2005.

Feely, R.A., L.D. Talley, G.C. Johnson, C.L. Sabine, and R. Wanninkhof, Repeat hydrography cruises reveal chemical changes in the North Atlantic. *Eos, Trans. AGU*, 86(42), 399, 404–405, 2005.

Feely, R.A., T. Takahashi, R. Wanninkhof, M.J. McPhaden, C.E. Cosca, S.C. Sutherland, and M.-E. Carr, Decadal variability of the air-sea CO_2 fluxes in the equatorial Pacific Ocean. *J. Geophys. Res.*, 111(C08), C08S90, doi: 10.1029/2005JC003129, 2006.

Hood, R.R., E.A. Laws, R.A. Armstrong, N.R. Bates, C.W. Brown, C.A. Carlson, F. Chai, S.C. Doney,
P.G. Falkowski, R.A. Feely, M.A.M. Friedrichs, M.R. Landry, J.K. Moore, D.M. Nelson, T.L. Richardson, B. Salihoglu, M. Schartau, D.A. Toole, and J.D. Wiggert, Pelagic functional group modeling: Progress, challenges and prospects. *Deep-Sea Res. Pt. II*, 53(5–7), 459–512, 2006.

Lee, K., L.T. Tong, F.J. Millero, C.L. Sabine, A.G. Dickson, C. Goyet, G.-H. Park, R. Wanninkhof,
R.A. Feely, and R.M. Key, Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. *Geophys. Res. Lett.*, 33, L19605, doi: 10.1029/2006GL027207, 2006.

McGillis (chair and ed.), W., R. Duce, D. Erickson, C. Fairall, D. Farmer, R. Feely, B. Huebert, W. Jenkins, W. Keene, R. Kiene, P. Matrai, K. Melville, W. Miller, R. Najjar, E. Saltzman, P. Schlosser, D. Siegel, W.-J. Cai, D. Ho, S. Doney, K. Johnson, C. McNeil, M.J. Perry, J. Prospero, O. Schofield, P. Shepson, D. Turk, and R. Wanninkhof, *The United States Surface Ocean—Lower Atmospheric Study (SOLAS), Science Implementation Strategy*. Published in collaboration with the US Ocean Carbon and Biogeochemistry (OCB) program and the International integrated Marine Biogeochemistry Ecosystem

Research (IMBER) and SOLAS programs, 123 pp., 2006.
Millero, F.J., *Chemical Oceanography*, 3rd Edition, CRC Press, 2006. Millero, F.J., T. B. Graham, F. Huang, H. Bustos-Serrano, D. Pierrot, Dissociation constants of carbonic acid in seawater as a function of salinity and temperature, *Mar. Chem.* 100, 80-94, 2006.

Millero, F.J., T. Graham, M. Chanson, J.M. Trapp, B. West, P. Gibson and D. Pierrot, *Global Ocean Repeat Hydrography Study: pH and Total Alkalinity Measurements in the North Pacific P16N February – March 2006*, Univ. of Miami Report, 2006.

Park, G.-H., K. Lee, R. Wanninkhof, and R. A. Feely, Ocean data-based estimates of recent year-to-year variability of oceanic uptake of CO_2, *J Geophys. Res.*, 111, doi:10.1029/2005JC003090, 2006.

Sabine, C.L., Global Carbon Cycle. In *Encyclopedia of Life Sciences*, John Wiley & Sons, Ltd., Chichester, http://www.els.net/ (doi: 10.1038/npg.els.0003), 2006.

Sabine, C.L., R.A. Feely, and R. Wanninkhof, Global Oceans: Ocean carbon. In State of the Climate in 2005, K.A. Shein (ed.), *Bull. Am. Meteorol. Soc.*, 87(6), S29–S30, 2006.

Sabine, C.L., and N. Gruber, Introduction to special section: North Pacific Carbon Cycle Variability and Climate Change. *J. Geophys. Res.*, 111(C7), C07S01, doi: 10.1029/2006JC003532, 2006.

Sweeney, C., E. Gloor, A.J. Jacobson, R.M. Key, G. McKinley, J.L. Sarmiento, R. Wanninkhof, Constraining global air-sea gas exchange for CO_2 with recent bomb ^{14}C measurements, *Global Biogeochem. Cycles*, in press, 2006.

Takahashi, T., S.C. Sutherland, R.A. Feely, and R. Wanninkhof, Decadal change of the surface water $pC0_2$ in the North Pacific: A synthesis of 35 years of observations. *J. Geophys. Res.*, 111(C7), C07S05, doi: 10.1029/2005JC003074, 2006.

Takahashi, T., F.J. Millero, R. Key, D. Chipman, E. Peltola, S. Rubin, C. Sweeney and S. Sutherland, *Determination of Carbon Dioxide, Hydrographic, and Chemical Parameters During the R/V Nathaniel B. Palmer Cruise in the Southern Indian Ocean (WOCE Section S04I, 3 May-4 July, 1996)*, prepared by Alex Kozyr, ORNL/CDIAC-150, NDP-086, March 2006.

Wanninkhof, R., The impact of different gas exchange formulations and wind speed products on global air-sea CO_2 fluxes, In *Transport at the Air Sea Interface*, edited by C. S. Garbe, et al., Springer, accepted, 2006.

Wanninkhof, R. D., S., Bullister, J. L., Gruber, N., Sabine, C., Feely, R. A., Johnson, G. C., Millero, F., Changes in Inorganic Carbon Inventory in the Atlantic Ocean over the Last Decade, *Eos Trans. AGU*, Ocean Sci. Meet. Suppl., 87, OS52C-01, 2006.

Wanninkhof, R., S. C. Doney, R. D. Castle, F. J. Millero, J. L. Bullister, D. A. Hansell, M. J. Warner, C. Langdon, G. C. Johnson, and C. W. Mordy, *Carbon dioxide, hydrographic and chemical data obtained during the R/V Ronald H. Brown repeat hydrography cruise in the Atantic Ocean: CLIVAR CO_2 section A16S_2005*, edited by A. Kozyr, p. 28, RNL/CDIAC-151NDP-087, 2006.

Wanninkhof, R., A. Olsen, and J. Triñanes, Air-Sea CO_2 Fluxes in the Caribbean Sea

from 2002-2004,
J. Marine Systems, Proceedings of the 37th International Colloquium on Ocean Dynamics: Gas Transfer at Water Surfaces, in press, 2006.
Wang, Z. A., X. Liu, R. H. Byrne, and R. Wanninkhof, Simultaneous Spectrophotometric Flow-Through Measurements of Multiple Inorganic Carbon Parameters in Seawater: At-sea Test and Comparison, in preparation.
Waugh, D.W., T.M. Hall, B.I. McNeil and R.M. Key, Anthropogenic CO_2 in the oceans estimated using transit-time distributions, *Tellus*, 58B(5), 376-389, 2006.